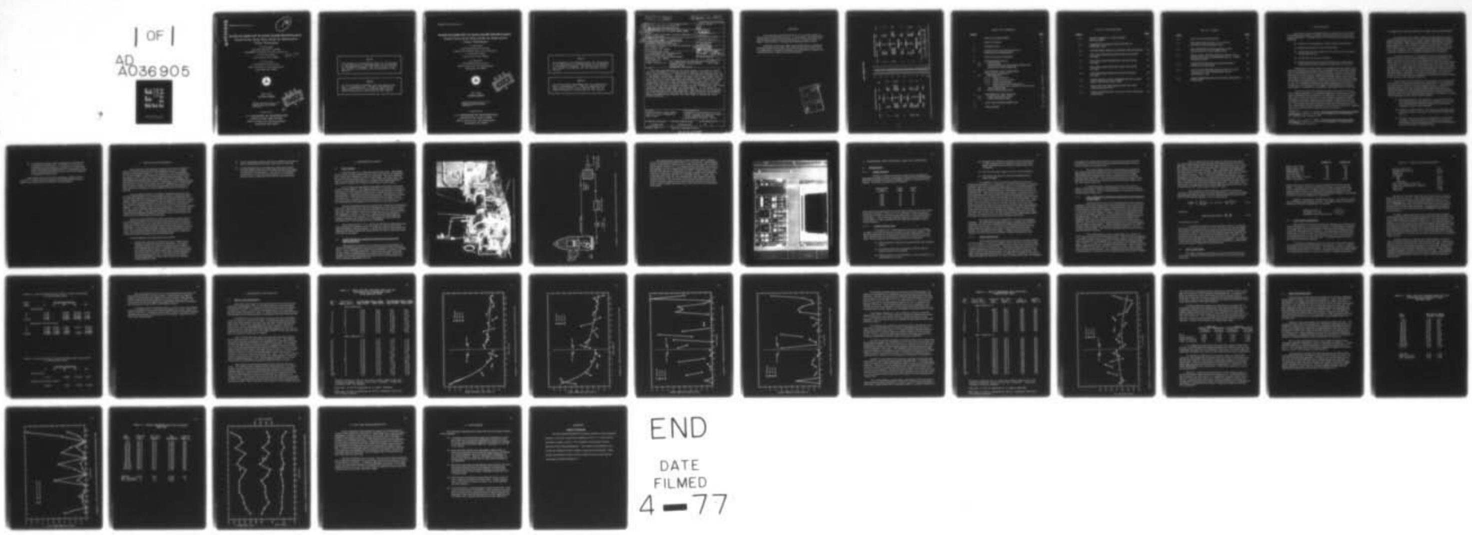
AD-A036 905 SOUTHWEST RESEARCH INST SAN ANTONIO TEX DEPT OF ENGIN--ETC F/G 21/4
WASTE OIL BURN-OFF IN COAST GUARD POWER PLANTS- DIESEL PISTON R--ETC(U)
JUL 76 J O STORMENT, J R SHERRARD DOT-TSC-920

UNCLASSIFIED SWRI-AR-1105 USCG-D-84-76 NL

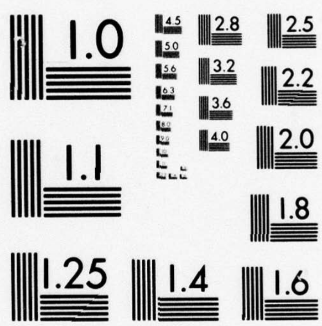
| OF |

AD
A036905



END

DATE
FILMED
4-77



MICROCOPY RESOLUTION TEST CHART

NATIONAL BUREAU OF STANDARDS-1963-A

REPORT NO. CG-D-84-76

10

WASTE OIL BURN-OFF IN COAST GUARD POWER PLANTS - Diesel Piston Ring Wear Study by Radioactive Tracer Techniques

J. O. Storment
Southwest Research Inst~~itute~~.,
Dep~~artment~~ of Engine and Vehicle Research
P. O. Drawer 28510
San Antonio Texas 78284

410 094

J. R. Sherrard
United States Coast Guard
Office of Research and Development
Washington DC 20590

JULY 1976
INTERIM REPORT

DOCUMENT IS AVAILABLE TO THE U.S. PUBLIC THROUGH THE NATIONAL TECHNICAL INFORMATION SERVICE, SPRINGFIELD, VIRGINIA 22161

Prepared for

U. S. DEPARTMENT OF TRANSPORTATION
UNITED STATES COAST GUARD
Office of Research and Development
Washington DC 20590

NOTICE

This document is disseminated under the sponsorship of the Department of Transportation in the interest of information exchange. The United States Government assumes no liability for its contents or use thereof.

NOTICE

The United States Government does not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

REPORT NO. CG-D-84-76

WASTE OIL BURN-OFF IN COAST GUARD POWER PLANTS - Diesel Piston Ring Wear Study by Radioactive Tracer Techniques

J. O. Storment
Southwest Research Institute
Department of Engine and Vehicle Research
P. O. Drawer 28510
San Antonio Texas 78284

J. R. Sherrard
United States Coast Guard
Office of Research and Development
Washington DC 20590

JULY 1976
INTERIM REPORT

Prepared for

U. S. DEPARTMENT OF TRANSPORTATION
UNITED STATES COAST GUARD
Office of Research and Development
Washington DC 20590

(18) USCG, TSC

(14) SwRI-AR-1105

Technical Report Documentation Page

1. Report No. (19) [redacted]-D-84-76, USCG-76-3	2. Government Accession No.	3. Recipient's Catalog No. (11)
4. Title and Subtitle (6) WASTE OIL BURN-OFF IN COAST GUARD POWER PLANTS- Diesel Piston Ring Wear Study by Radioactive Tracer Techniques.		5. Report Date Jul[redacted]76
		6. Performing Organization Code AR-1105
7. Author(s) (10) J.O./Storment [redacted] J. R./Sherrard		8. Performing Organization Report No. DOT-TSC-USCG-76-3
9. Performing Organization Name and Address Southwest Research Institute* Department of Engine and Vehicle Research P.O. Drawer 28510 San Antonio, TX 78284		10. Work Unit No. (TRAIS) CG607/R6001
		11. Contract or Grant No. (15) DOT-TSC-920 new
12. Sponsoring Agency Name and Address U.S. Department of Transportation United States Coast Guard Office of Research and Development Washington, DC 20590		13. Type of Report and Period Covered (9) Interim Report. June [redacted]75 - March [redacted]76,
		14. Sponsoring Agency Code

15. Supplementary Notes

*Under contract to: U.S. Department of Transportation Transportation Systems Center Kendall Square Cambridge, MA 02142

(12) 44p.

16. Abstract

The work reported here is the final effort in a study to determine the feasibility of burning waste crankcase lubricating oils in Coast Guard powerplants. Specifically, the program reported here was to determine if burning a mixture of used lube oil and diesel fuel in a two-stroke cycle diesel engine resulted in increased rates of ring wear relative to that observed with standard fuel. Piston ring wear rates were measured by the radioactive tracer technique. Four top compression rings of a Detroit Diesel 6-71 engine were made radioactive, and the wear particles present in the crankcase oil from these rings were measured by gamma ray spectrometry. In 210 hours of operation, using diesel fuel with used lube oil up to 10% by volume, no increased wear rates were measured. The engine was disassembled upon test completion, and the wear and deposit build-up on critical engine components were nominal for this type of engine and total operating hours.

17. Key Words	18. Distribution Statement
Diesel Engines, Coast Guard, Lube Oil, Fuel Consumption, Engine Wear	Document is available to the U.S. Public through the National Technical Information Service, Springfield, Virginia 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	43	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

410094

6B

PREFACE

This work was performed for the U. S. Coast Guard Office of Research and Development and the U. S. Department of Transportation. The Technical Contract Monitor for the latter organization was R. A. Walter, Staff Member of Transportation Systems Center of DOT.

Installation of the test engine and instrumentation, mechanical work performed on the engine, and conduct of the tests was by Victor E. Poggemoeller, Research Assistant in the Department of Engine and Vehicle Research, Southwest Research Institute.

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F

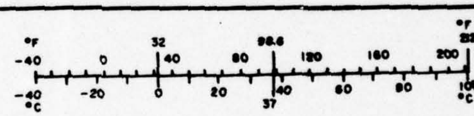


TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

1. INTRODUCTION

This report is the concluding effort of a study for the Coast Guard to determine the feasibility of burning off waste lubricating oils in Coast Guard powerplants. Previous reports [1,2] in this effort accomplished the following:

(1) Solicited recommendations of diesel engine manufacturers,

(2) Studied existing lube oil burn-off programs,

(3) Investigated fuel requirements for Coast Guard diesel engines, boilers and turbines.

(4) Tested waste oil clean-up methods,

(5) Measured the emissions and performance of a diesel engine when burning various mixtures of waste lube oil in fuel oil.

Manufacturers of four-stroke cycle engines generally approve this method of oil disposal and some even recommend the oil treatment method prior to mixing with the fuel oil for their engines. However, some manufacturers of two-stroke cycle engines warn against the use of the lube oil/ fuel mixture in their engines, since the two-stroke engine is particularly susceptible to the formation of combustion chamber deposits that can cause piston rings and exhaust valves to stick and air ports in the cylinder liners to clog. It is thought that burning even small quantities of used lube oil can promote the formation of such deposits with subsequent poor engine performance, increased fuel consumption, and higher rates of ring wear.

Since two-stroke cycle engines constitute a majority of the Coast Guard engine population, it was deemed important to investigate the wear effects resulting from this method of oil disposal on a two-stroke engine. This report covers the results of a study utilizing a radioactive tracer technique to determine wear effects on the upper compression rings of a two-stroke cycle diesel engine burning mixtures of waste lube oil in fuel oil. The radioactive tracer technique permits wear determinations to be made with minimum engine operating time and extreme sensitivity; measured wear rates of less than 10^{-3} grams per hour are typical.

[1] Hobbs, J. R., and R. A. Walter, Lubricating Oil Burn-Off In Coast Guard Powerplants, Report No. CG-D-80-75, Department of Transportation - U. S. Coast Guard, February 1975.

[2] Hobbs, J. R., and R. A. Walter, Waste Oil Burn-Off In Coast Guard Powerplants, Report No. CG-D-78-76, Department of Transportation - U. S. Coast Guard, June 1976.

2. RADIOACTIVE TRACER METHOD OF WEAR RATE MEASUREMENT

The radioactive tracer (RAT) method of measuring wear rates is a proven laboratory test and research tool that is applicable to any fluid-wetted mechanical system (e.g., engine, pump, gear train) that contains metal components. The component of interest is irradiated by neutron bombardment in a nuclear reactor in order to produce one or more artificial radioisotopes. The physical dimensions and metallurgical properties of the component are not changed by this process, and thus the component's performance in the parent mechanism is not affected.

In an actual wear test, the mechanical system is operated at the desired condition, which is usually defined by values of rotational speed (rpm), load (mechanical stress), and temperature (thermal stress). Small radioactive wear particles accumulate in the fluid operating medium or lubricant at a rate that is directly proportional to the wear rate of the component. To insure that all of these wear particles remain in the fluid medium (a necessary condition to accurately reflect the actual wear rate of the component), no filtration of the fluid is performed. For wear tests involving engine components, this means that oil filters are not used; however, air and fuel filters are employed to minimize the engine's intake of air- and fuel-borne abrasive particles.

The activity of the lubricant due to accumulation of the radioactive wear debris is measured by a gamma ray spectrometer, and calculations are performed to obtain the wear rate (see Section 5). Test results are generally used to select (or screen) candidate lubricants, fuels, or component designs for more extensive laboratory or field evaluations. The RAT method of wear measurement has several advantages over conventional wear tests that render it highly suitable as a screening technique. These advantages can be summarized as follows:

(1) The measurement is very sensitive. Wear rates of 10^{-3} to 10^{-6} gram per hour, depending on the specific activity (radioactive disintegrations per unit mass per unit time) of the component, can be easily measured.

(2) Tests are of short duration. The wear rate associated with a given test condition can usually be determined in eight hours or less.

(3) The wear rate can be read out continuously on a strip chart recorder. Incipient failure of the radioactive part due to catastrophic wear will quickly register on the instrumentation and can be avoided by stopping the test.

(4) It is possible in some cases to measure wear rates of two components simultaneously. For instance, wear from a chromeplated piston ring and a standard iron or steel ring can be determined simultaneously due to the presence of two distinct radioisotopes and the ability of the instrumentation to distinguish between them.

These points in favor of the RAT technique, together with the fact that it is commonly and regularly used at Southwest Research in engine wear studies, led to its selection in this program.

3. TEST PLAN AND RATIONALE

The test plan for this program was based on the three characteristics of the RAT method of wear determination that make it a highly effective screening technique: (1) the sensitivity of the measurement, (2) the short length of operating time required to obtain a stabilized wear rate datum, and (3) the wear rate can be monitored continuously, thus eliminating the possibility that catastrophic wear of the component will go unnoticed until actual failure occurs. Therefore, it was initially decided that a series of tests--each of which could be completed in a normal eight-hour work day--would be conducted with a baseline fuel and with two or three test fuels consisting of various mixtures (ratios) of used lube oil and fuel.

It was realized that this brief length of operating time with each test fuel would probably not be long enough to produce a significant amount of combustion deposits in terms of conventional wear measurement techniques. However, it was thought that with the sensitivity of the RAT method, even the short-duration tests would reveal any significant increase in wear rate (relative to baseline values) caused by use of a given lube oil/fuel mixture. If an increase in wear rate was observed, it could then be assumed that use of such a mixture would be equally detrimental to the piston rings on a long-term basis. This assumption follows from the reasonable conclusion that any deposits formed by combustion of the mixture would only worsen with increased engine operating time.

However, it was decided that if the short-duration tests revealed no significant differences in wear rates for the baseline and test fuels, a longer test (greater than, say, 100 hours' duration) would be conducted to determine if there were any long-term effects associated with use of the mixed fuel. Use of the RAT technique would still be advantageous for such a test since no other method permits continuous observation of the wear rate. As it turned out, such a test was judged necessary to confirm the results of the short-duration tests and was performed.

The test phases of the program were as follows:

I. Twenty-five (25) short-duration tests were conducted with baseline fuel and three test fuels (mixtures). Two engine operating conditions--defined by speed and power output--were utilized (see Section 5). Repeated tests (in most cases, two tests performed consecutively) were conducted with each oil-to-fuel ratio, with one or two baseline tests separating the tests with each test fuel. This order of tests demonstrated repeatability of results and revealed any change in the baseline wear rate.

II. Six (6) consecutive baseline tests were conducted to determine day-to-day repeatability of wear rates with the same fuel.

III. A long-duration test was performed to determine if there were any effects from use of the mixed fuel that had not been revealed in the shorter tests. This long test was preceded and followed by a short-duration baseline test in order to obtain a better comparison of the effects of the mixed fuel.

4. EXPERIMENTAL SETUP

4.1 TEST ENGINE

A Detroit Diesel 6-71 engine was used in this study. This engine model is used in large numbers by the Coast Guard and can be considered as a "worst case" situation in regard to ring wear. This last statement derives from the fact that the 6-71 is a two-stroke cycle engine and, also, that for a given operating condition, a smaller diesel engine generally experiences a higher rate of ring wear than does a larger engine.

A 6-71 engine was furnished by the sponsor from the Coast Guard stock of rebuilt engines. The engine underwent a brief period of break-in operation at the Coast Guard rebuild facility and was furnished in ready-to-run condition. The engine was mounted on a test stand (Figure 4.1) and instrumented to obtain all pertinent operating data, including fuel consumption mass rate. The engine was operated briefly on the stand to check basic performance figures and the correctness of the installation; it was then disassembled and prepared for the radiotracer ring wear tests.

The top compression ring was selected for irradiation and subsequent wear test, based on the fact that this ring undergoes more severe service than do the other rings and is most susceptible to any pro-wear conditions that exist in the cylinder. Seven such rings were sent to a nuclear reactor and irradiated for about 13.5 days at a neutron flux of approximately 1.5×10^{13} per cm^2 per second. The rings were steel with chromium-plating on the wear face only; hence, radioisotopes of iron (Fe^{59}) and chromium (Cr^{51}) were produced by this irradiation.

Four pistons (Nos. 1, 3, 4, and 6) were fitted with radioactive rings since this was the maximum number of rings that could be used without special shielding around the engine. Only the top ring on these pistons was replaced; the lower compression rings and the oil control rings were those that came in the engine.

4.2 RADIOTRACER OIL SAMPLING SYSTEM AND GAMMA RAY SPECTROMETER

Measurement of radioactive wear debris was accomplished by a special oil sampling system and associated radiation detection instrumentation. The oil sampling loop (Figure 4.2) consisted of a pump to circulate oil at a steady rate (approximately 1.3 gpm) from the engine oil sump, through a lead-shielded sensing well and back to the sump. Engine oil filters were not used during the wear tests so that the radioactive wear debris remained suspended in the oil.

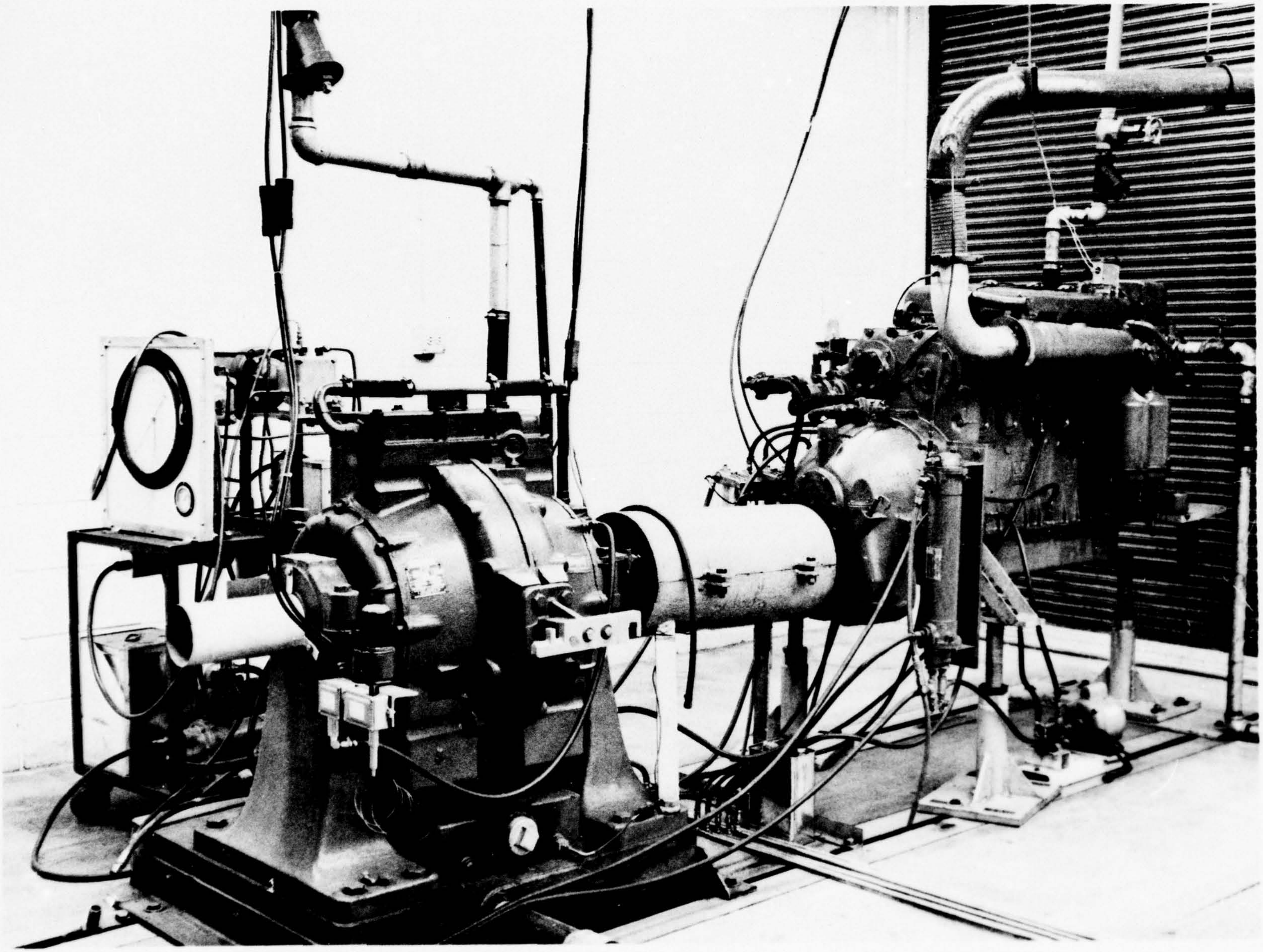


FIGURE 4.1 DETROIT DIESEL 6-71 TEST ENGINE INSTALLATION

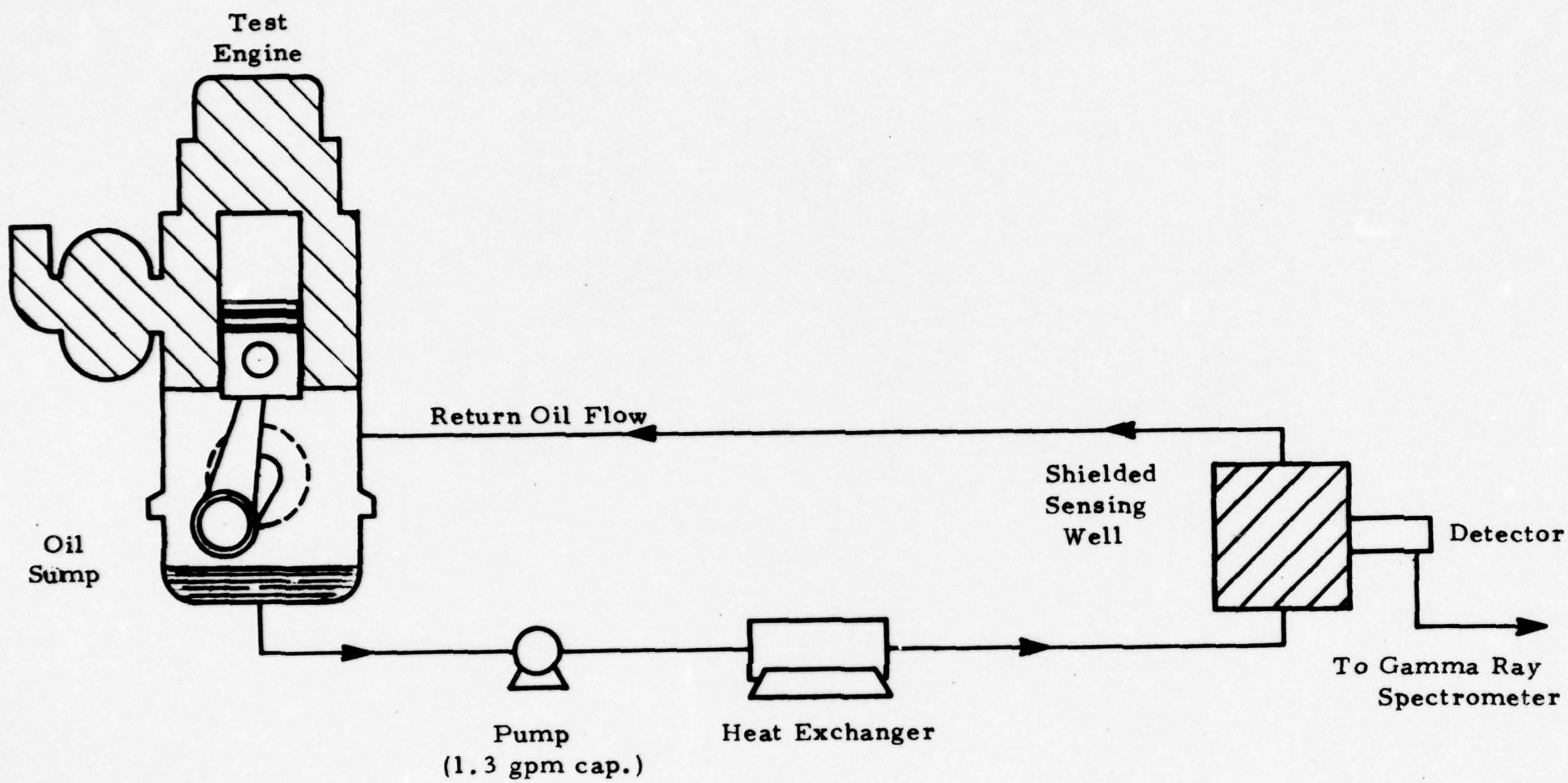


FIGURE 4.2 SCHEMATIC OF RADIOACTIVE TRACER OIL SAMPLING LOOP

The sensing well contained a NaI(Tl) (sodium iodide, thallium activated) scintillation detector with a 3 x 3 inch crystal. After amplification, output from the detector was routed through a gamma ray energy spectrometer (Figure 4.3). Two single channel analyzers were used; one analyzer was set to register the activity of the isotope iron 59 (Fe^{59}) and the other was set for chromium 51 (Cr^{51}). Output from each unit went into a ratemeter, and the time-averaged signals were displayed on a dual-pen strip chart recorder as counts per minute, or cpm. One-minute duration counts for each channel were also displayed digitally. In actual practice, the one-minute counts from the digital meter were used to calculate reported wear rates, and the strip chart traces were used to warn of sudden increases in the wear rate and as documentation of the tests.

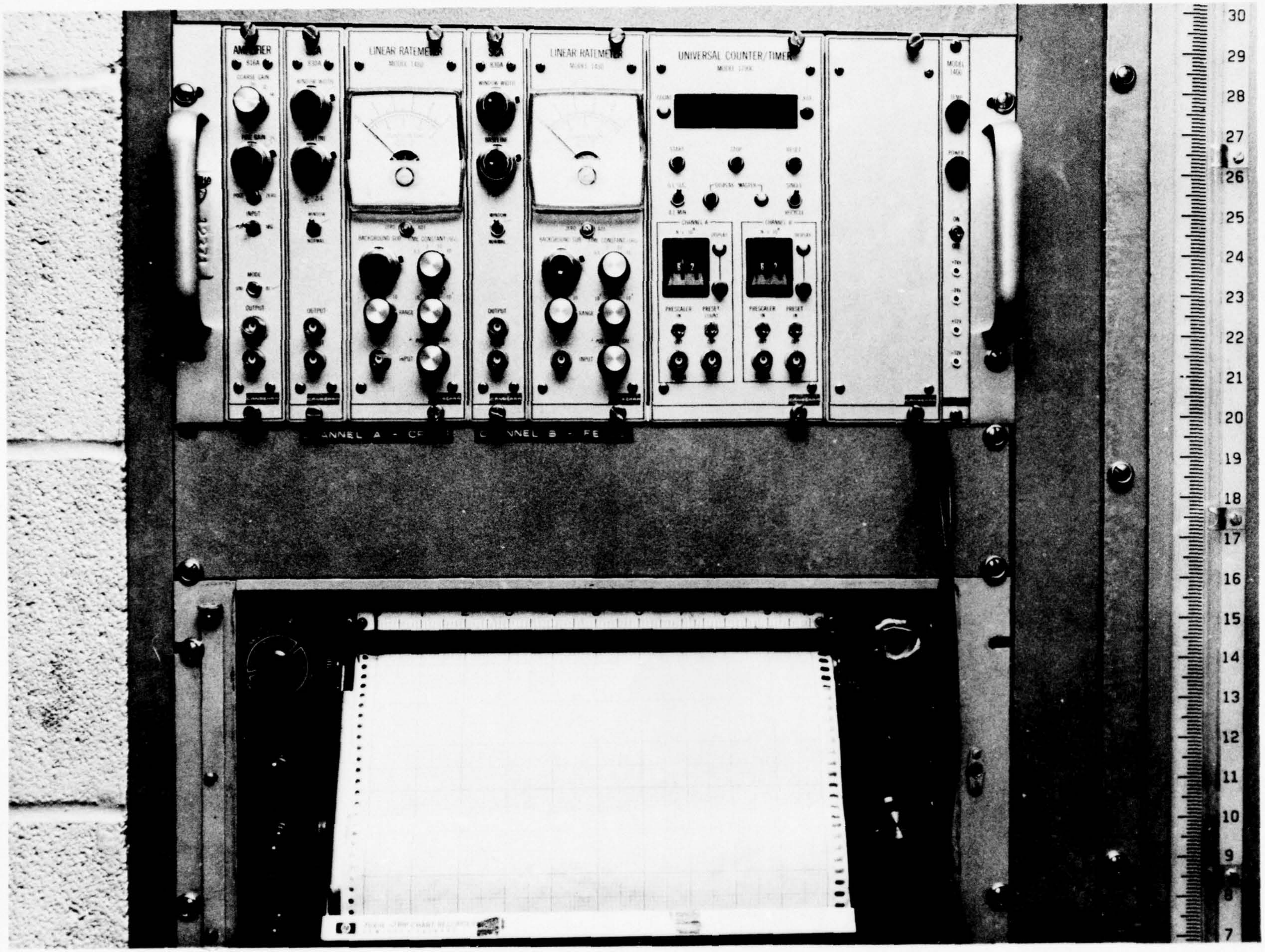


FIGURE 4.3 TWO-ISOTOPE GAMMA RAY ENERGY SPECTROMETER

5. PROCEDURES, TEST CONDITIONS, FUELS AND LUBRICANTS

5.1 PROCEDURES

5.1.1 Engine Break-In

Break-in of the new radioactive rings was accomplished by operating the engine in modes characterized by gradually increasing speed and brake mean effective pressure (BMEP), which is a measure of ring loading. The break-in sequence was as follows:

Engine Speed, RPM	Power, BHp	BMEP, psi
1000	15	14
1200	26	20
1500	40	25
1600	52	30
1800	77	40
1600	100	58

Each mode was maintained for one to two hours except for the last, which lasted for four hours. Wear rate of the radioactive rings was closely monitored to detect any abnormal wear during this critical initial period of operation. Since wear rate stabilized quickly to a nominal level at each condition, it was concluded that the rings had undergone a satisfactory break-in.

5.1.2 Conduct of Wear Tests

In a sequence of short-duration wear tests it is important to conduct each test according to a specific, unvarying procedure. This approach eliminates the introduction of extraneous variables into these very sensitive tests and minimizes the carry-over effect from previous tests. In this program, the following procedure was employed:

(1) Check operation of gamma ray spectrometer with radiation source.

(2) Fill engine sump with five gallons of lube oil and run engine at idle for five minutes.

(3) Begin operation at Test Condition I or II (see Section 5.2) with baseline or test fuel.

(4) Maintain test condition for balance of day (seven hours) to obtain maximum wear effect due to fuel; record all engine operating data and ambient condition data every 15 minutes.

(5) Stop test and allow engine to idle for several minutes.

(6) Stop engine and allow oil sump and sampling loop to drain overnight.

In a sequence of wear tests which employs lube oil as the independent variable (e.g., a program to evaluate effectiveness of several crankcase lubricants in inhibiting engine wear), it is common practice to flush the engine and sampling loop with either the day's test lubricant or a neutral flush oil (no wear inhibitors or dispersants) before the start of each wear test. This step accomplishes two things: it removes any trace of the previous day's test oil from the engine and sampling loop, and it also removes any wear debris (particularly the radioactive type) that might "hang up" in the system and not be removed by the overnight drain. However, since the crankcase oil was the same type for all tests in this program, no oil flush was necessary, and the overnight drain effectively removed almost all radioactive wear debris from the engine and sampling loop. The latter fact was established by filling the engine sump with oil, starting the circulation of oil through the sampling loop, and observing the count rate for this "new" oil both before and immediately after engine start-up. The always-low count rate signified that no appreciable amount of radioactive debris was left from the previous wear test.

The long-duration test consisted of 127 hours of continuous operation. The only special requirement was to replenish the consumed crankcase oil; this was accomplished by adding small quantities of oil three times per 24 hours. The amount of oil required per day was calculated from the known (from previous short-duration tests) brake specific oil consumption of the engine. Adding oil every 8 hours of operation kept the sump level relatively constant throughout the test.

5.1.3 Engine Maintenance

The engine functioned perfectly throughout the program except for two incidents. In the first incident, which occurred at the end of Test No. 26, an injector tip fractured (the fracture marks were clearly visible) at a point inside the injector body. This allowed almost the entire tip, a cylinder-shaped piece of metal about 1/2 inch in diameter and 1-1/4 inch long, to fall into the engine cylinder when the engine was operating. The piston and both exhaust valves had to be replaced. Fortunately, the piston rings (including the radioactive top ring) and cylinder liner were not damaged.

The engine was rebuilt and operated for several hours with oil filters connected in order to remove any loose debris that resulted from the injector failure or the repair work.

The second engine problem occurred during an attempt to run a final seven-hour baseline test after the 127-hour endurance test. This problem involved the failure (due to a broken tube) of a small watercooled heat exchanger that cools the lubricant in the reversing reduction gear drive unit. This problem did not affect the engine in any way that could influence the ring wear and merely caused a delay of one day in the start of that test.

It should be noted, especially in the case of the injector failure, that neither problem was attributable to use of the lube oil/fuel mixture in the engine. In fact, neither problem occurred when the engine was operating on mixed fuel.

5.1.4 Mass Calibration of Gamma Ray Spectrometer and Calculation of Wear Rates

Each detection circuit of the instrumentation system produced readings in counts per minute which were proportional to the mass of the particular wear metal (containing its isotope) present in the sensing well. It was therefore necessary to calibrate each circuit in terms of the mass of chromium or iron present in the well. This was accomplished by use of a set of calibration solutions. These solutions were prepared by dissolving pieces of chromium and iron, which had been irradiated along with the piston rings, in acid. The acid solutions were then diluted with distilled water until various densities (in g/ml) of each material were obtained. Each of the Cr and Fe solutions was placed in the sensing well and a reading in cpm obtained. These readings were plotted as a function of mass, and a straight line, obtained by a least-squares fit, was calculated for these points. This was the calibration line for the chromium and iron detection circuits.

The calibration also served to determine the "overlap" of Fe^{59} radiation into the Cr^{51} detection channel. (This overlap is composed of secondary radiation effects, produced by the higher energy Fe^{59} gamma rays, that register in the channel set to detect the lower energy gamma rays of Cr^{51}.) As each Fe^{59} solution was placed in the shielded sensing well, a reading in cpm was obtained for both channels. A plot of cpm in the Fe^{59} channel versus cpm in the Cr^{51} channel was made, and a straight line was fitted to these points. This calibration line was used to correct the observed Cr^{51} count rate for the overlap produced by the Fe^{59} present.

The so-called relative wear rates (in cpm/hr) for Cr and Fe were determined by calculating straight lines (least-squares fit) for the cpm data. This relative wear rate was then corrected in two ways. First, the contribution of Fe^{59} to the observed Cr^{51} count was determined from the calibration mentioned previously. This contribution was subtracted from the gross Cr^{51} count, and the resulting net Cr^{51} count was corrected for radioactive decay. This was done by assuming that the first test occurred on "Day Zero" (i.e., full isotope activity was present), and then multiplying each subsequent test result by the decay factor for that test day. The datum that resulted from these two corrections was the corrected relative wear rate of the chromium-plated ring faces. The relative wear rate for the iron ring sides was corrected only for radioactive decay, since the presence of Cr^{51} had no effect on the Fe^{59} count.

The so-called absolute wear rate, expressed as mass per unit time, was derived from a corrected relative wear rate (A) by a simple calculation involving the slope (B) of the instrument calibration curve for Cr^{51} or Fe^{59} and the quantity of oil (C) in the system:

$$A \ \frac{\text{cpm}}{\text{hr}} \times \frac{1}{B} \ \frac{10^{-7}\ \text{g}}{\text{ml-cpm}} \times (C \times 10^{4}\ \text{ml}) = \frac{AC}{B} \ \frac{10^{-3}\ \text{g}}{\text{hr}} \quad . \tag{5-1}$$

Therefore,

$$\text{Absolute Wear Rate} = \frac{AC}{B} \ \frac{\text{mg}}{\text{hr}} \tag{5-2}$$

for chromium or iron.

It should be noted that normal procedure involves calculating wear rate for the last two hours of a test, when the wear rate has usually been stable for several hours preceding this period and the test variable (in this case, the lube oil in the fuel) has had the maximum available time to produce its effect. This practice was followed here. However, wear rates were also calculated for the last six hours of each test; i.e., only the first hour's cpm data were omitted from the calculation. The purpose of this second calculation was to determine if repeatability of some of the wear rates could be improved by this procedure.

5.2 TEST CONDITIONS

Two engine operating conditions were used in the short-duration wear tests. Typical operating parameter values with baseline fuel were as follows:

	Condition I	Condition II
Engine speed, RPM	1600	2000
Engine power, BHp	100	165
Engine BMEP, psi	58	74
Oil sump temp., F	205	230
Water out temp., F	172	178
Fuel consumption, lb_m/hr	50	82
BSFC, lb_m/bhp-hr	0.500	0.497

Both speed-power points lie on a typical propeller load curve for this engine. Condition I was used for the first 13 tests; it was then decided to go to maximum power at a higher speed in order to obtain wear rate and performance data at a condition characterized by higher fuel consumption rate and increased mechanical and thermal stresses. Accordingly, the last 20 tests were conducted at Condition II.

Intake air temperature, barometric pressure, and absolute humidity were at ambient values during all tests. The range of values of these air properties during the program were as follows:

Intake air temp., F	80 ± 15
Barometer, in. Hg	29.30 ± 0.30
Humidity, grains H_2O/lb_m Air	75 ± 25

5.3 FUELS AND LUBRICANTS

Short duration tests were conducted with baseline fuel and with lube oil/fuel mixtures of 3, 6, and 10% by volume. The 6% figure is specified as an upper limit by some manufacturers of four-stroke engines, and the 3 and 10% values effectively bracket it. The previously-mentioned feasibility study of a lube oil burn-off program for the Coast Guard advocated a maximum mixture of 1%; hence, the three ratios used in this study can be considered as worst-case conditions. The long-duration (127-hour) test was run with the 6% mixture.

A standard commercial-grade DF-2 fuel was used as the baseline fuel and as the fuel for mixing with the used lube oil. Table 5.1 contains the results of an analysis of this fuel. The test fuel meets the requirements of Federal Specification VV-F-800B. The lube oil used in the engine sump was a high-grade series CC oil that meets MIL-L-2104B specifications.

TABLE 5.1 TEST FUEL SPECIFICATIONS

Gravity, °API at 60 F	35.7
Specific gravity at 60 F	0.846
Cetane No.	52.12
Distillation	
50%	500 F
90%	589 F
End Point	649 F
Heat of Combustion, BTU/lb_m	19,467
Particulate Contamination, mg/liter	2.3
Sulfur, %wt.	0.006
Ash, %wt.	0.005

The batch of used lube oil for the short-duration wear tests was supplied by the Coast Guard. This oil was obtained from a two-stroke cycle turbocharged Fairbanks Morse main propulsion engine of the USCGC Sherman and, after being diluted about two-to-one with diesel fuel, was put through a bilge water separator which removed solid contaminants down to about ten-micron size. Approximately 140 gallons of this treated used oil and fuel mixture was shipped to SwRI in three 55-gallon drums.

At SwRI, a sample was taken from each drum (after thorough mixing) and subjected to elemental analysis by X-ray fluorescence, both as a straight liquid and as material retained by a 0.45 micron filter. The results of this analysis are given in Table 5.2. The concentrations of chlorine, zinc, and calcium for the liquid sample are below the maximum permitted for lubricating oils that meet MIL-L-9000G specifications. The concentration of sulfur is slightly above the maximum permitted under this specification; however, some of this sulfur probably came from the diesel fuel that was mixed with the oil. Iron concentration (due to engine wear) was judged to be nominal for oil that had been used for a considerable length of time.

The three barrels of used oil were mixed together in order to obtain a uniform batch for further dilution with diesel fuel. Before each wear test with the mixed fuel, the amount of lube oil required for the particular mix ratio was combined with fuel in a clean drum. Mixing was accomplished by stirring and by pumping the mixture through a pair of standard GM diesel fuel filters and back into the drum. This pumping continued throughout the test to assure that the mixture remained homogeneous and that particulate matter was kept at minimum attainable concentration.

TABLE 5.2 ANALYSIS RESULTS FOR USED CG LUBE OIL DILUTED 2:1 WITH DIESEL FUEL

Barrel Code	Element Concentration				
	S	Cl	Fe	Zn	Ca
Liquid Sample					
A	0.37%	-	50 ppm	290 ppm	0.21%
B	0.35%	-	20 ppm	250 ppm	0.16%
C	0.32%	-	60 ppm	230 ppm	0.18%
Average	0.35%	-	43 ppm	257 ppm	0.18%
Retained by 0.45 micron filter					
A	67 ppm	24 ppm	16 ppm	10 ppm	244 ppm
B	24 ppm	10 ppm	5 ppm	-	62 ppm
C	23 ppm	9 ppm	5 ppm	-	68 ppm
Average	38 ppm	14 ppm	9 ppm	3 ppm	125 ppm

TABLE 5.3 ANALYSIS RESULTS FOR USED SWRI LUBE OIL DILUTED 2:1 WITH DIESEL FUEL

	Element Concentration				
	S	Cl	Fe	Zn	Ca
Liquid Sample					
	0.21%	-	30 ppm	400 ppm	0.06%
Retained by 0.45 micron filter					
	38 ppm	-	9 ppm	33 ppm	113 ppm

The second batch of used oil, for the long-duration wear test, was obtained from the local city bus company. The bus fleet is composed entirely of two-stroke cycle engines, and the oil used in these engines meets all Detroit Diesel specifications, as well as MIL-L-2104B. The drain period for these bus engines is approximately 400 hours of operation and corresponds to about 5000 to 6000 miles of travel.

A sample of this oil, diluted by DF-2 to a ratio of 2:1, was analyzed in the same manner as the Coast Guard-furnished oil, and the results are shown in Table 5.3. Comparison with Table 5.2 shows that the two samples generally have similar concentrations of key elements, especially in the case of the liquid samples.

6. DISCUSSION OF TEST RESULTS

6.1 SHORT-DURATION TESTS

Total mass wear rates for chromium (face) and iron (side) of four radioactive compression rings for the short-duration (seven-hour) tests are presented in Table 6.1. Ring face (Cr) mass wear rates are plotted in Figures 6.1 and 6.2, while the corresponding data for the ring side (Fe) are plotted in Figures 6.3 and 6.4. Since the data are quite numerous, this discussion will deal principally with general trends and considerations.

It should first be remarked that all of the wear rates are thought to be low, even for a total of four rings. Dividing each wear rate by four shows the small amount of wear per hour that each ring underwent during these tests. Some of the calculated wear rates for a given time period were so low as to be indistinguishable from zero; however, since it is obvious that the rings must have been undergoing some wear, the rates in question have been labeled "Nil" rather than "Zero". In any case, the wear rates so termed are less than 0.01 mg/hr.

Next, note that the wear rates are sometimes radically different for the last two hours of a test than for the last six hours. The changes that result from this recalculation can sometimes be interpreted in terms of what was happening to the wear rate within a given test. For example, for the first three tests (on baseline fuel) it is apparent that the Cr wear rate was increasing during the latter portion of Test No. 1 (two-hour value greater than six-hour value), was stable for all of Test No. 2 (wear rates virtually identical), and was decreasing slightly during the last part of Test No. 3 (two-hour value less than six-hour value). This type of analysis can be carried out for all the test results, but, unfortunately, it does not yield a meaningful pattern. And, from inspection of both two-hour and six-hour data, repeatability of results is improved little, if at all.

Data scatter is particularly apparent in the ring side (Fe) wear rates. The reason for the variability is not known; however, this characteristic has been observed in other programs involving both diesel and gasoline engines. It has been speculated that radioactive wear particles from the ring sides tend to collect (or hang up) in the ring grooves in the piston and are flushed out of the grooves and into the crankcase at an irregular rate. In contrast, wear particles from the ring faces are thought to enter the crankcase without hang up and at the rate they are produced by the wear process. Hence, face wear rates behave in a more regular manner.

TABLE 6.1 TOTAL FACE AND SIDE WEAR RATES FOR FOUR RADIOACTIVE TOP COMPRESSION RINGS-- SHORT-DURATION TESTS

Test No.	Oil-to-Fuel Ratio, Vol. %	Cr Face Wear Rate, mg/hr		Fe Side Wear Rate, mg/hr	
		Last 2 Hrs.	Last 6 Hrs.	Last 2 Hrs.	Last 6 Hrs.
	Test Condition I				
1	0	0.98	0.62	Nil	Nil
2	0	0.90	0.86	0.26	0.84
3	0	0.77	0.88	Nil	Nil
4	6	0.39	0.34	0.95	0.18
5	6	0.42	0.42	0.38	0.11
6	0	0.47	0.40	0.08	Nil
7	10	0.24	0.23	0.07	0.14
8	10	0.22	0.22	0.18	0.27
9	0	0.32	0.34	1.20	0.25
10	0	0.24	0.27	0.30	0.19
11	3	0.15	0.18	0.06	0.08
12	3	0.27	0.24	Nil	Nil
13	0	0.21	0.22	0.09	0.03
	Test Condition II				
14	0	0.36	0.34	1.22	1.37
15	0	0.38	0.51	0.90	0.11
16	3	0.34	0.42	Nil	0.14
17	3	0.30	0.35	1.37	0.35
18	0	0.29	0.21	0.72	0.62
19	0	0.32	0.24	1.93	1.38
20	6	0.38	0.28	1.06	0.06
21	6	0.18	0.22	Nil	Nil
22	0	0.27	0.50	0.27	0.19
23	0	0.29	0.28	0.28	0.08
24	10	0.21	0.27	Nil	0.02
25	10	0.13	0.15	Nil	0.27
26*	0	0.32	0.29	0.11	Nil
27	0	0.26	0.26	1.27	0.68
28	0	0.26	0.21	1.03	0.74
29	0	0.19	0.23	1.20	0.59
30	0	0.19	0.20	0.25	0.19
31	0	0.22	0.22	Nil	0.25
32+	0	0.25	0.27	2.16	0.54
33**	0	0.21	0.09	0.96	1.71

*Injector failed at end of this test; engine rebuilt with new piston and exhaust valves in one "hot" cylinder. Rings and cylinder liner not damaged.

+Test Nos. 31 and 32 separated by 11 weeks' downtime.

**Test Nos. 32 and 33 separated by 127-hr. endurance test with 6% oil/fuel mixture.

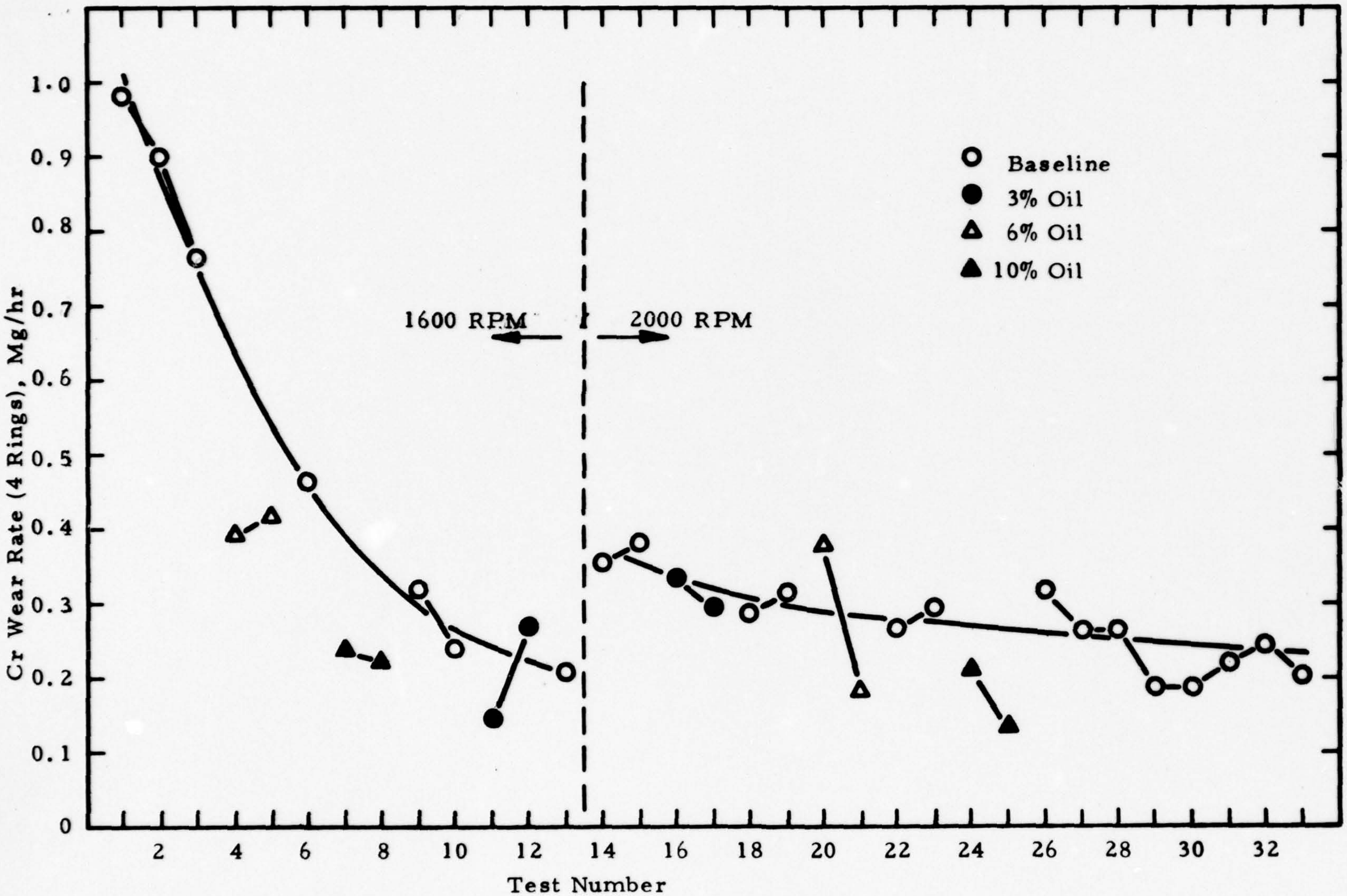


FIGURE 6.1 RING FACE WEAR RATES FOR LAST TWO HOURS OF TEST

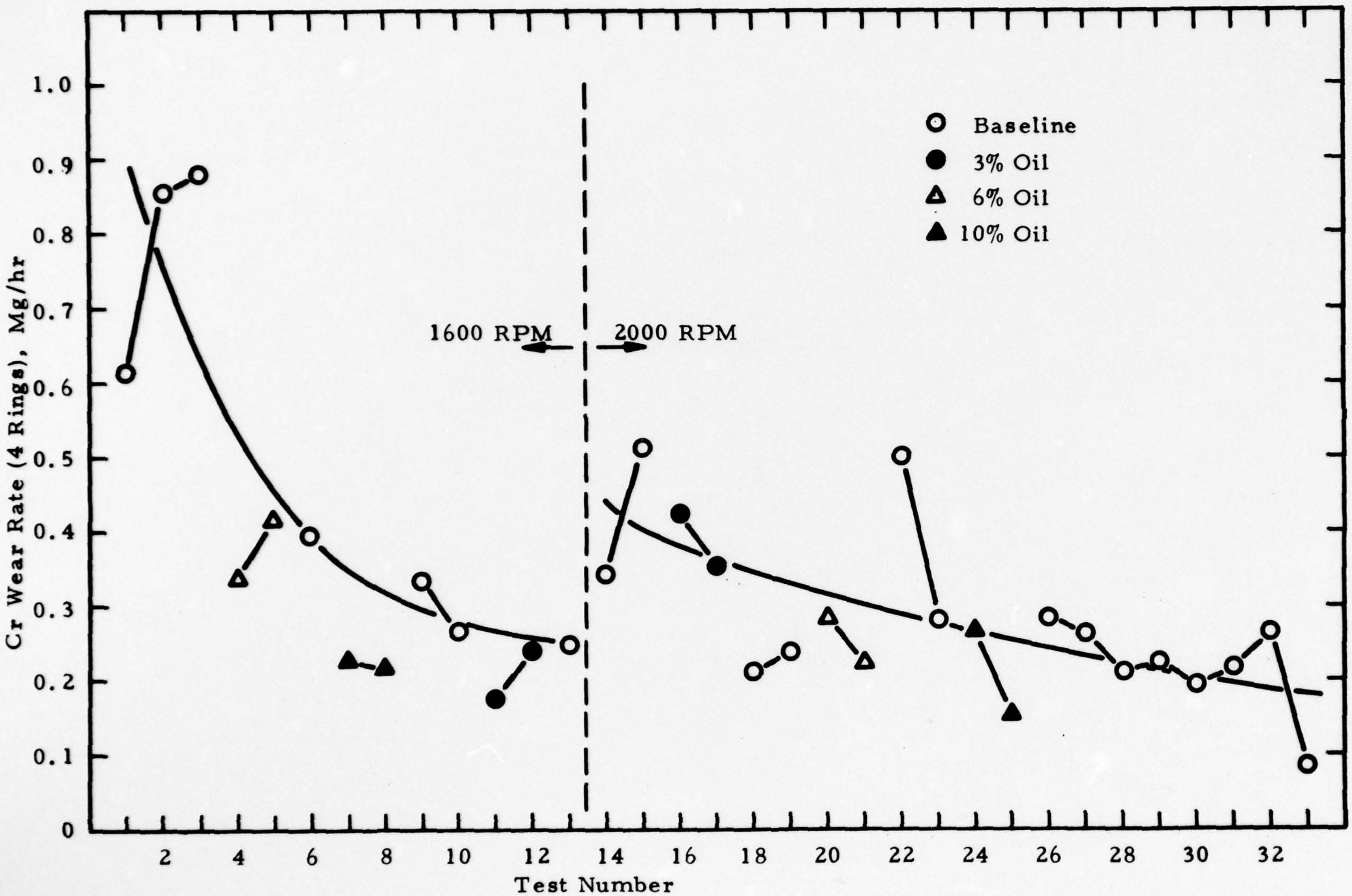


FIGURE 6.2 RING FACE WEAR RATES FOR LAST SIX HOURS OF TEST

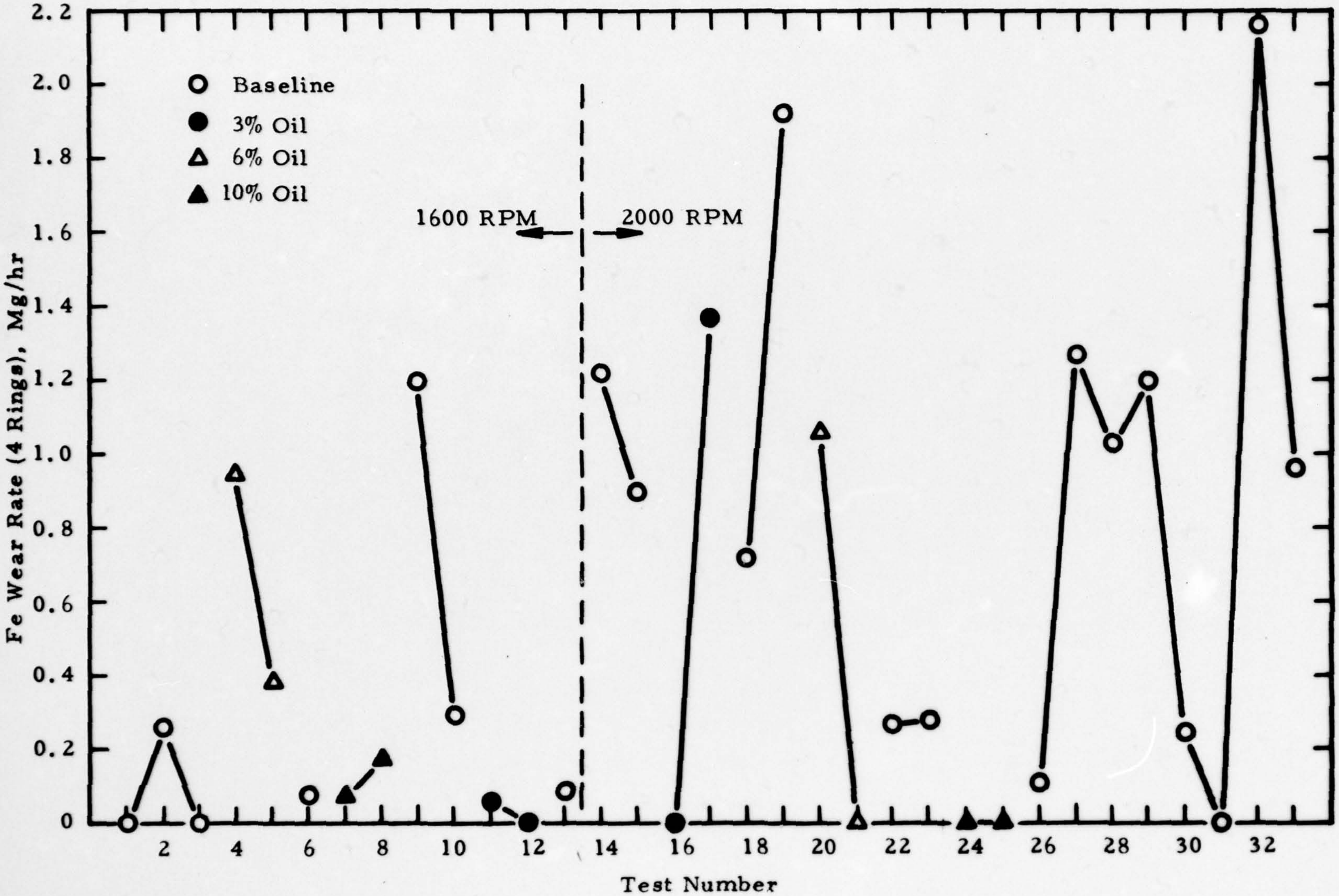


FIGURE 6.3 RING SIDE WEAR RATES FOR LAST TWO HOURS OF TEST

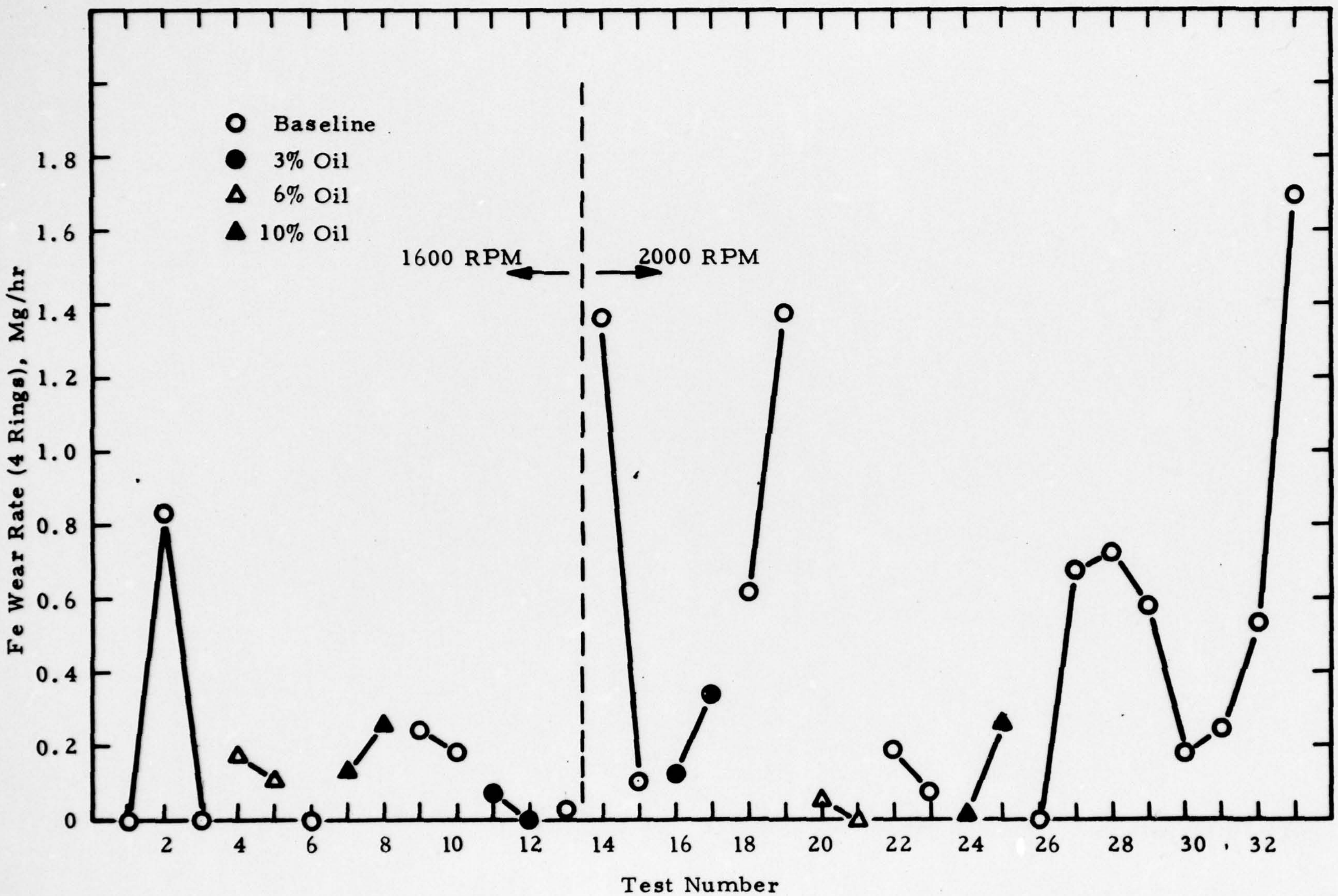


FIGURE 6.4 RING SIDE WEAR RATES FOR LAST SIX HOURS OF TEST

Even though ring face wear rates are more closely grouped, they exhibit a certain amount of variability in both two-hour and six-hour calculations. However, the factor that complicates interpretation of the data is the change in the baseline wear rate. This shift in the baseline is most likely due to carry-over effect (i.e., the characteristics of the previous test are reflected in the following test) which, in turn, is caused by the changes in test fuel. Since determination of the exact magnitude of the carry-over effect is not possible, it was decided to present these data in a manner that, to some extent, took the change in the baseline into account.

Accordingly, Figures 6.1 and 6.2 feature a smooth, downward-sloping curve that is an "eyeball" best fit through the baseline wear rates; i.e., it follows the trend of the wear rates during the particular test sequence. (Such a curve fit was not attempted for the highly variable ring side wear rates.)

It is apparent that, when this downward trend is allowed for, face wear rates for the mixed fuel are either (1) unambiguously less than or equal to the baseline wear rates, or (2) higher than the baseline values by an amount that is no greater than the normal variation in these baseline values. That is, the use of mixed fuel does not obviously increase wear of the top compression ring face under the two test conditions.

In order to put this conclusion on a firmer basis, a test to determine the statistical significance of differences in Cr wear rates for baseline and mixed fuel was made. Since they are so few in number, all six wear rates obtained with mixed fuel were grouped together (and statistically treated) as "non-baseline" wear rates. The statistical test consisted of the application of Student's t-distribution to test the hypothesis that the mean values of the two sets of wear data are equal. A 5% level of significance was selected; that is, there is a 1 in 20 chance of rejecting a true hypothesis.

Results of this analysis show that the mean values of baseline and mixed fuel Cr wear rates are <u>not</u> statistically different. This means that face wear data for a given test condition (either I or II) are not significantly different. Therefore, it is concluded that use of mixed fuel did not result in wear rates that were different from those obtained with baseline fuel. Note that in this analysis, data for the last two hours of the tests were compared and data for the last six hours were compared, but not to each other; i.e., the reference time frame was held constant to avoid comparing dissimilar data.

The corresponding average engine performance data for the short-duration wear tests are presented in Table 6.2, and the most important of these data, brake specific fuel consumption (BSFC), is shown in Figure 6.5.

TABLE 6.2 ENGINE PERFORMANCE DATA FROM SHORT-DURATION WEAR TESTS

Test No.	Oil-to-Fuel Ratio, Vol. %	Observed BHp	Fuel Cons., lb_m/hr	SFC, lb_m/BHp-hr	Exhaust Temp., F
	Test Condition I				
1	0	98.4	49.8	.506	568
2	0	100.2	49.9	.498	584
3	0	99.3	49.9	.503	586
4	6	99.2	50.5	.509	616
5	6	98.8	51.9	.525	647
6	0	99.3	50.1	.505	622
7	10	99.4	51.6	.519	632
8	10	99.2	52.6	.530	653
9	0	99.3	51.6	.520	643
10	0	100.3	50.0	.499	617
11	3	99.3	50.1	.505	596
12	3	99.2	51.1	.515	623
13	0	99.4	50.6	.509	619
	Test Condition II				
14	0	164.9	83.0	.503	818
15	0	168.5	83.3	.494	802
16	3	166.7	84.0	.504	801
17	3	164.6	83.9	.510	814
18	0	163.7	82.8	.506	822
19	0	163.9	82.6	.504	816
20	6	163.4	83.9	.513	802
21	6	163.4	83.8	.513	803
22	0	167.9	83.2	.496	806
23	0	168.6	82.9	.492	805
24	10	164.4	84.0	.511	802
25	10	162.7	83.8	.515	800
26*	0	164.8	83.2	.505	815
27	0	165.8	81.2	.490	799
28	0	166.6	81.3	.488	807
29	0	168.3	81.5	.484	804
30	0	170.2	81.6	.479	798
31	0	170.0	81.7	.481	801
32+	0	166.6	83.7	.502	825
33**	0	158.9	81.8	.515	823

*Injector failed at end of this test; engine rebuilt with new piston and exhaust valves in one "hot" cylinder. Rings and cylinder liner not damaged.

+Test Nos. 31 and 32 separated by 11 weeks' downtime.

**Test Nos. 32 and 33 separated by 127-hr. endurance test with 6% oil/fuel mixture.

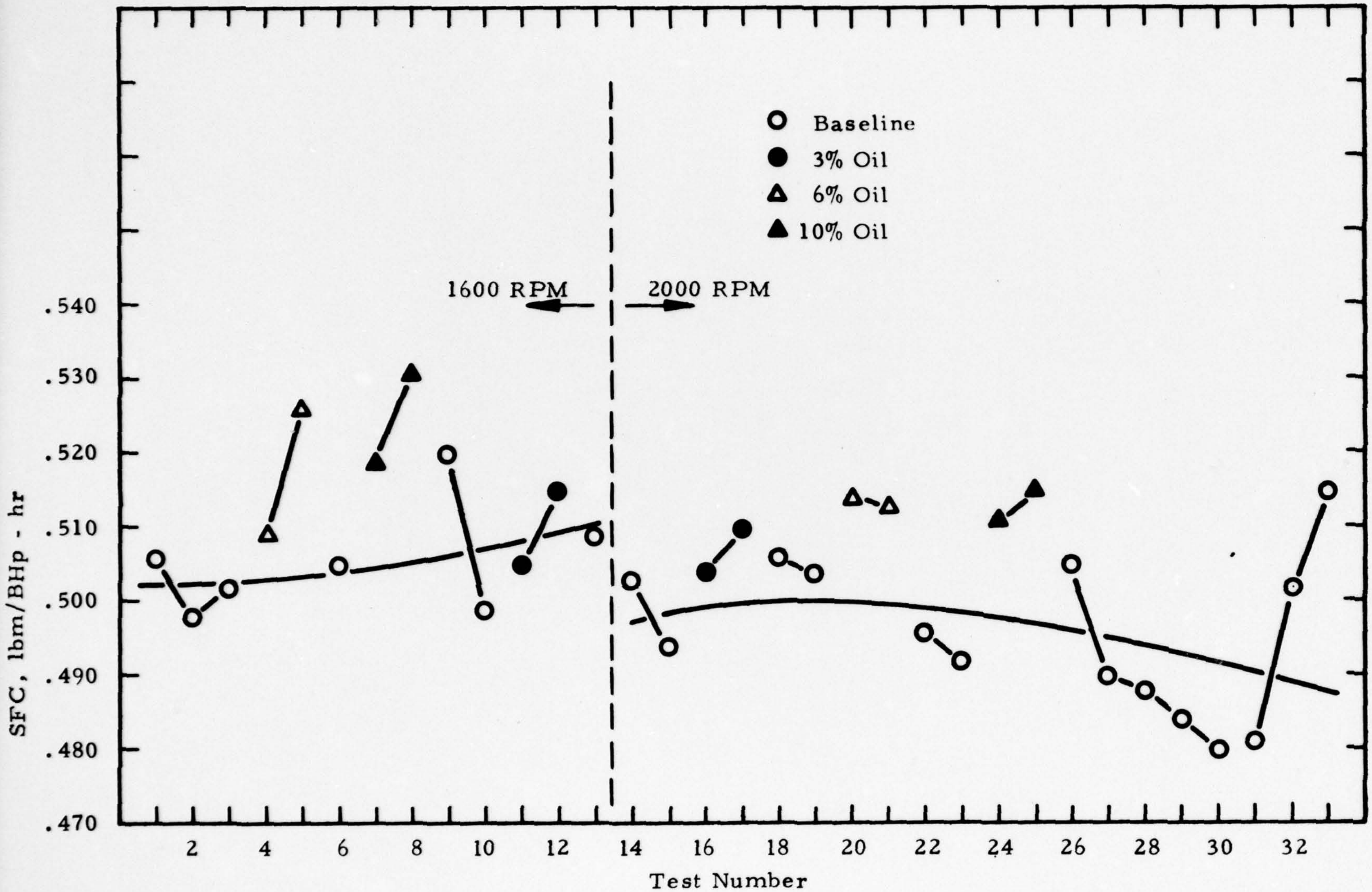


FIGURE 6.5 BRAKE SPECIFIC FUEL CONSUMPTION DATA FROM SHORT-DURATION WEAR TESTS

The curved lines on this graph again represent an "eyeball" best fit of the test-by-test values of BSFC obtained with baseline fuel. It appears that BSFC was higher for those tests conducted with the mixed fuel and, furthermore, that this increase was greater for increasing amounts of oil in the fuel. However, the small number of test points for mixed fuel make strict determination of this effect difficult.

A simple statistical analysis was performed on the BSFC data in an attempt to determine the significance of the observed differences. To simplify this analysis, the data from tests with mixed fuel were again lumped together and treated as if they were obtained from tests with an oil-to-fuel ration that is the average of the three ratios actually used, i.e., (3% + 6% + 10%) ÷ 3 = 6.3%. This approach was also dictated by the fact that only two tests were conducted with each oil/fuel ratio at each test condition. Results of this analysis are summarized below:

	1600 rpm		2000 rpm	
	Baseline Fuel (7 Tests)	Mixed Fuel (6 Tests)	Baseline Fuel (14 Tests)	Mixed Fuel (6 Tests)
Mean	0.506	0.517	0.496	0.511
Mean Deviation	0.005	0.008	0.009	0.003
Standard Deviation	0.007	0.009	0.011	0.004
Coeff. of Variation	1.4%	1.7%	2.2%	0.8%

It is evident that each group of data has only a slight amount of dispersion: mean deviation and standard deviation are both low, and the latter represents only about one to two percent of the mean. The mean values for mixed fuel are higher by 2.2% and 3.0% at 1600 and 2000 rpm, respectively.

To determine if differences in the mean values are statistically significant, the hypothesis is made that the mean values are the same; then, the test with Student's t-distribution is performed, again at a 5% level of significance. This test reveals that at both 1600 and 2000 rpm, the mean values <u>are</u> different at the chosen level of significance. Therefore, it is highly likely that the use of mixed fuel, in the ratios tested here, results in increased BSFC.

However, it must be remembered that, on the average, some 6.3 percent by volume of this mixed fuel is used lube oil. Since densities of the oil and fuel are very close, it is acceptable to assume that the mixed fuel is 6.3 percent lube oil by mass. Hence, the engine is actually consuming about six percent less diesel fuel and producing two to three percent less power, a situation that is similar to derating an engine by reducing fuel consumption.

6.2 LONG-DURATION TEST

Total mass wear rates for the four rings for the 127-hour endurance test are given in Table 6.3 and shown in Figure 6.6. Wear rates have been calculated for each eight-hour period and plotted as a point at the end of that period. It is evident that the wear rates vary from one eight-hour period to the next, that ring side wear rate varies more than face wear rate, and that variations in both wear rates are somewhat larger in magnitude than those exhibited by data from the short-duration tests. Since the endurance test was conducted without engine shut-down or a change in fuel (the two most important factors in the carry-over effect), these variations are likely related to uncontrolled (and, in all likelihood, uncontrollable) factors in the wear test.

Ring wear rates were judged to be nominal throughout the test. The abrupt increase in both face and side wear during the last eight hours is not thought to be indicative of ring distress or impending catastrophic failure due to ring scuffing; this conclusion is supported by the fact that wear rates returned to normal levels in the seven-hour baseline test conducted after the endurance run. This would not have been the case had the radioactive rings undergone a significant change in their wear profile or if a significant amount of combustion deposits had accumulated in the ring area.

The average performance data for each eight-hour period of the endurance tests are contained in Table 6.4 and shown in Figure 6.7. Power and BSFC underwent a slight degradation, especially in the last 40 or so hours. Fuel consumption rate was almost constant throughout the test and was not a factor in the changes in power or BSFC.

A least-squares straight line was calculated for the BSFC values, and the percentage rate of increase of this line was found to be about 1.2% per 100 hours of engine operation. Of course, it is not possible to say if this rate of increase would have held constant had the test continued. It is interesting to note that, like ring wear rate, BSFC increased markedly in the last eight hours of the test. However, unlike the wear rate, BSFC did not return to a lower value in the short-duration baseline test that followed the endurance run (see Table 6.2 or Figure 6.5).

TABLE 6.3 TOTAL FACE AND SIDE WEAR RATES FOR FOUR RADIOACTIVE TOP COMPRESSION RINGS--ENDURANCE TEST

Test Hours	Wear Rate, mg/hr	
	Cr Face	Fe Side
0-8	0.06	1.00
8-16	0.04	Nil
16-24	0.18	Nil
24-32	0.17	0.32
32-40	0.08	Nil
40-48	0.02	Nil
48-56	0.38	1.43
56-64	Nil	Nil
64-72	0.13	0.48
72-80	0.24	1.24
80-88	Nil	Nil
88-96	0.08	1.06
96-104	0.39	0.65
104-112	Nil	Nil
112-120	0.30	1.06
120-127	0.81	2.64
Average	0.18	0.62
Mean Deviation	0.15	0.59
Std. Deviation	0.21	0.68

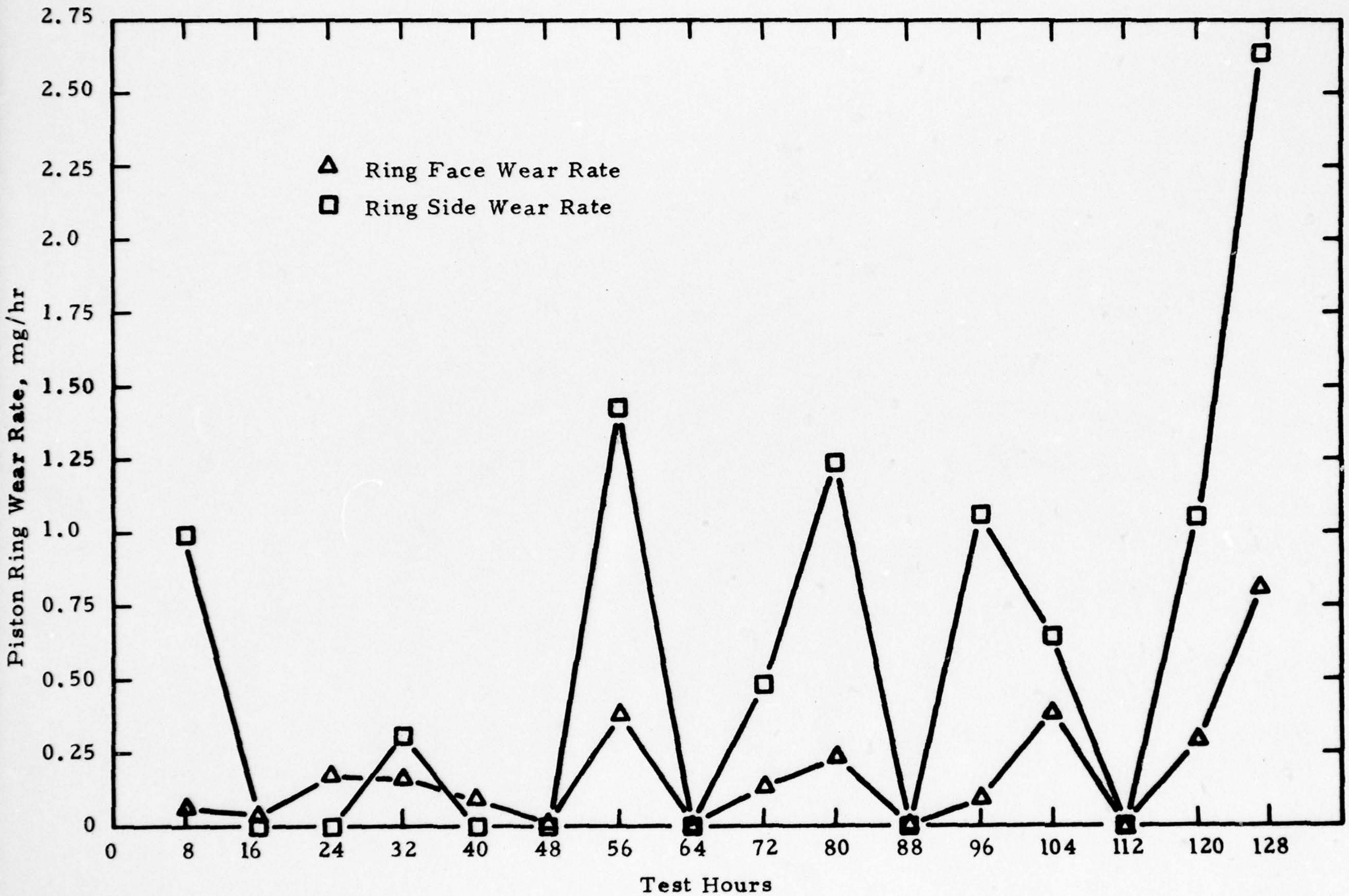


FIGURE 6.6 RING FACE AND SIDE WEAR RATES FOR LONG-DURATION WEAR TEST

TABLE 6.4 ENGINE PERFORMANCE DATA FROM ENDURANCE WEAR TEST

Test Hours	Observed BHp	Fuel Cons. lb_m/hr	SFC, $lb_m/BHp\text{-}hr$	Exhaust Temp., F
0-8	163.4	83.4	0.510	850
8-16	161.7	83.1	0.514	845
16-24	161.8	83.4	0.516	837
24-32	161.5	83.5	0.517	842
32-40	160.8	83.6	0.520	843
40-48	160.4	83.4	0.520	843
48-56	160.9	83.6	0.520	850
56-64	162.0	83.7	0.517	839
64-72	162.2	83.4	0.514	834
72-80	159.6	83.3	0.522	852
80-88	161.0	83.6	0.519	842
88-96	161.7	83.1	0.514	836
96-104	159.0	83.1	0.523	847
104-112	161.0	83.3	0.517	836
112-120	160.5	83.4	0.519	835
120-127	157.2	82.8	0.527	839
Average	160.9	83.4	0.518	842
Mean Deviation	1.0	0.2	0.003	5
Std. Deviation	1.4	0.2	0.004	6

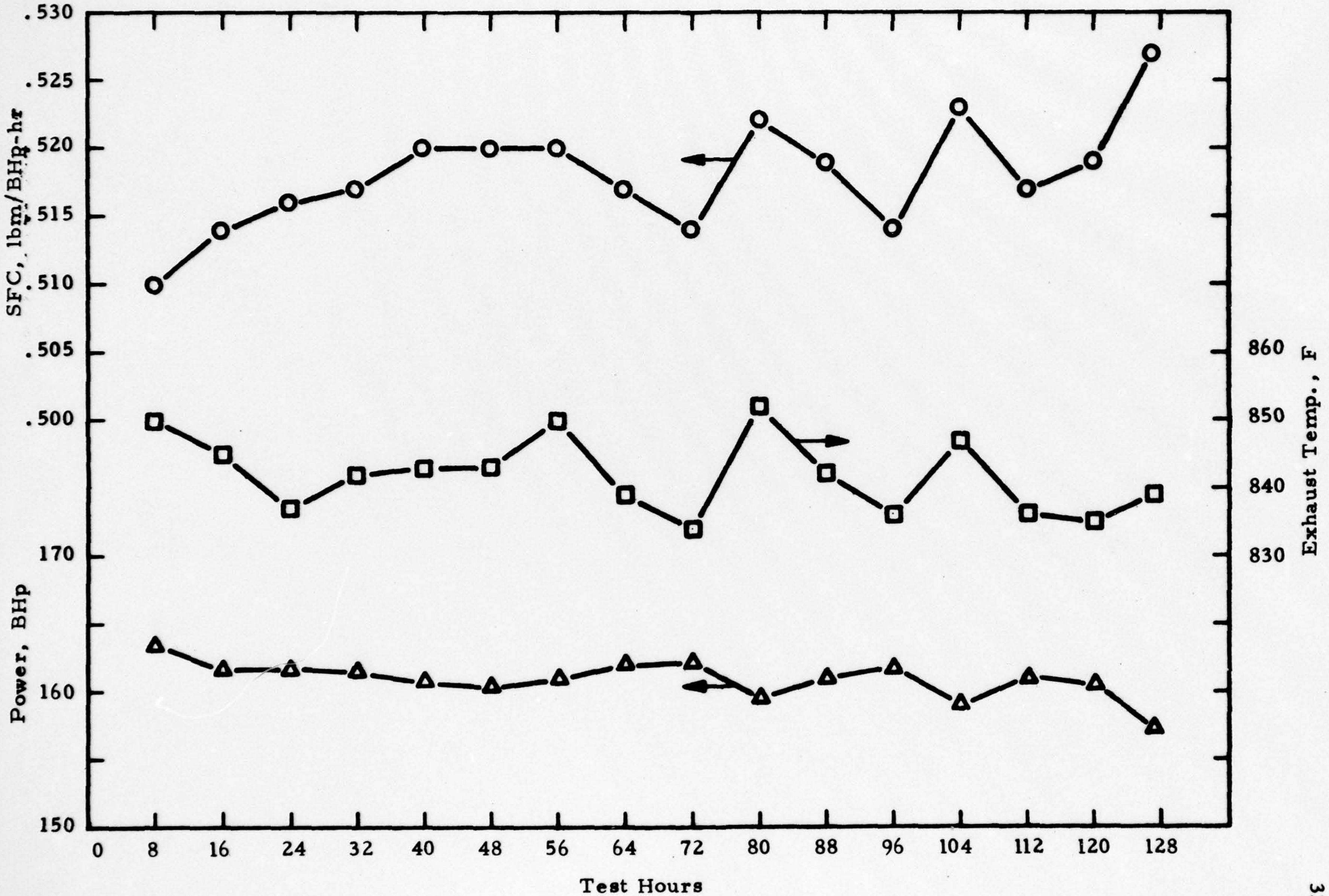


FIGURE 6.7 ENGINE PERFORMANCE DATA FOR LONG-DURATION WEAR TEST

7. POST-TEST ENGINE INSPECTION

At the conclusion of the program the engine was disassembled for removal of the radioactive rings and for visual inspection of critical engine components. Pistons, rings, injectors, liner ports, and valves were examined to determine if use of the mixed fuel had resulted in excessive formation of combustion deposits. This inspection was strictly qualitative in nature since it involved a relative comparison between the condition of the test engine and that of other two-stroke cycle engines which have been disassembled in the SwRI laboratory after operating on standard diesel fuel. It should be mentioned, however, that most of the engines inspected in the past have accumulated 500 to 1000 hours of operation, whereas the test engine had about 375 hours of total running time, of which about 210 hours was with the mixed fuel.

With this qualifying factor in mind, it was decided by SwRI personnel that the buildup of deposits was not obviously excessive and should, therefore, be described as "nominal". In addition, <u>all</u> piston rings (not just the radioactive top compression rings) and cylinder liners showed only a very slight amount of wear; of course, this result might be expected because of the low observed wear rates of the radioactive rings.

8. CONCLUSIONS

The following conclusions were drawn from the test results obtained in this program:

(1) A sequence of short-duration (seven-hour) radioactive tracer wear tests did not reveal any significant differences in wear rate of the top compression rings when the engine was operated on baseline fuel and oil/fuel mixtures containing 3, 6, or 10% oil by volume.

(2) Observed brake specific fuel consumption (BSFC) data for these short-duration tests showed that engine power decreased 2 to 3% from baseline value for equal mass consumption of the oil/fuel mixture. However, the engine was actually consuming about 6% less diesel fuel by mass when operating on the mixed fuel.

(3) Ring wear rates observed throughout a long-duration (127-hour) test with 6% oil/fuel ratio did not undergo any substantial increase until the last few hours; however, the wear rates returned to lower levels during a subsequent seven-hour test on baseline fuel.

(4) BSFC deteriorated during the long-duration test at a rate of about 1.2% per 100 hours of running time. Unlike ring wear rates, BSFC did not return to a lower value in the baseline test that followed.

(5) Visual inspection of critical engine components (pistons, rings, injectors, liner ports, and valves) at the conclusion of the program revealed only a nominal amount of deposit formation for an engine of this type that had operated for this length of time (375 hours total, of which 210 hours were with mixed fuel).

APPENDIX

Report of Inventions

The work performed under this contract produced no new inventions. However, a new fuel conservation technique for the U. S. Coast Guard is described on pages 1 and 28. This technique is the burning of waste lube oil in Coast Guard powerplants. This report also documents a new use for the radioactive tracer method of ring wear measurement. Specifically, this method is used to measure piston ring wear when burning waste lube oils mixed with fuel oil.